Automatic Construction of Accurate Models of Physical Systems

1996 Progress Report 29 August 1996

ONR #N00014-96-1-0720

PI: Elizabeth Bradley

University of Colorado

(303) 492-5355 `lizb@cs.colorado.edu`

Other Team Members:

Matthew Easley	graduate student	Ph.D.	computer science
Apollo Hogan	undergraduate student	B.A.	comp. sci. and math
John Lawrence	undergraduate student	B.A.	applied math
Agnes O'Gallagher*	NIST		Mathematician
Janet Rogers*	NIST		Computer Scientist
Reinhard Stolle*	graduate student	Ph.D.	computer science
Laura Vidal	admin assistant		

* Most of Stolle's funding is through another grant. Rogers and O'Gallagher are paid by NIST; they are devoting a few hours a week to consultations with our group as problems arise when we call their code from our programs.

FY96 Numerical Productivity Measures:

Refereed papers submitted but not yet published:	1
Refereed papers published:	1
Unrefereed reports and articles:	none
Books of parts thereof submitted but not yet published:	none
Books of parts thereof published:	none
Patents filed but not yet granted:	none
Patents granted:	none
Invited Presentations:	1
Contributed Presentations:	1
Honors Received:	none
Prizes or Awards Received:	none
Promotions obtained:	comprehensive reveiw/contract renewal
Graduate Students Supported:	1
Post-docs Supported:	equipment
Minorities Supported:	1

2. Project Summary

Traditional system identification addresses the task of inferring a mathematical model of a system from observations of that system. A controls engineer might perform this task, in its most basic form, by choosing a power series and matching its coefficients, via some sort of regression, to a numerical time series from a sensor. The goal of this project is the development of a computer program, called PRET, that automates the entire system identification process, at several levels, by building an artificial intelligence (AI) layer on top of a set of traditional system identification techniques. This AI layer executes many of the high-level parts of the identification process that are normally performed by a human expert, using qualitative, symbolic, and geometric reasoning to perform *structural identification*, intelligently guiding the search to the proper type and form of equation. Unknown coefficients are then found with established *parameter identification* techniques.

PRET works with ordinary differential equation (ODE) models, linear or nonlinear, in one variable or many. Its implementation is a hybridization of traditional numerical analysis methods, such as simulation and nonlinear regression, with AI techniques like logic programming, symbolic computation, computer vision techniques, and qualitative reasoning. The input consists of specific information about an individual system, in three forms:

- the user's hypotheses about the physics involved
- observations, interpreted and described by the user, symbolically or graphically, in varying formats and degrees of precision
- physical measurements made directly and automatically on the system

To construct an ODE model from this information, PRET combines powerful mathematical formalisms, such as the link between the divergence of an ODE and the friction of the system that it describes, with domain-specific notions — such as force balances in mechanical systems — to allow the types of custom-generated approximations that are lacking in existing AI modeling programs. Two different sets of rules, both of which may easily be changed or augmented by the user, play critical roles in the model-building task. Domain-specific rules are used to combine hypotheses into models — a nontrivial task in a system with more than one degree of freedom, or a system in which physical effects couple to one another — while general rules about ODE properties are used by a custom logic system to infer facts from models and from observations. Both model- and observation-based inferences are governed by specifications, which prescribe the resolution for quantities of interest. Any contradictions between the set of facts inferred from the observations and the set of facts inferred from a candidate model cause that model to be ruled out, in which case PRET tries a new combination of hypotheses. The first noncontradictory model in this sequence is returned as the answer.

Acting upon relatively simple mechanics examples like the ones found in the first chapters of standard system identification texts, the currently implemented version of the program can use these techniques to construct accurate ODE models. Tools that only solve textbook problems in a single domain, however, are not very useful; the ultimate goal of this line of research is a tool that can construct a model of high-dimensional black-box systems, drawn from any domain that admits ODE models, using only information that is observable from the ports of those systems. In order for PRET to attain the next level of this ambitious plan, a variety of

significant improvements — the subject of the work to be performed under this contract — are necessary. These fall in four general areas, as listed below:

1. Expand PRET's capability to handle more-complex systems in several more domains (electronics, viscoelastics, chemical kinetics, etc.), more efficiently, using a richer rule set.

2. Use the proof trees maintained by the logic system (which document all of the reasoning that has been performed), together with discrepancy-driven reasoning, to add or remove terms from models that requires refinement or simplification.

3. Develop and incorporate a set of power-series techniques to synthesize hypotheses automatically — an idea that is ubiquitous in system identification but completely absent from the AI modeling literature — and to infer internal state variables.

4. Develop and incorporate analysis and control techniques to actively and realistically exploit sensors and actuators to allow a true *input-output* approach to modeling, another idea that is relatively common in system identification but rare in AI.

When this contract began in April 1996, PRET incorporated only a few rules and had only been used by one person to model two examples — the driven pendulum and a system of three springs and two masses. Since then, several people have used PRET to model several other systems. The streamlining, debugging, and general improvement forced by this evolution from a single-user tool to one routinely used by an entire group represented a significant advance. Experience with those new examples also led us to incorporate a variety of new rules into PRET and required significant (and unforeseen) improvements in the parameter estimation process, which took on two forms:

- increased sophistication in PRET's automatic interaction with ODRPACK, the Fortran code written by Janet Rogers and Agnes O'Gallagher of NIST that we use to determine parameter values

- suggestions for improvements in ODRPACK itself that arose as a result of our interactions

During this period, we also developed some simple computer-vision techniques for processing of sensor data and incorporated them into PRET — a significant step in item 4 above — and began work on the power-series techniques of item 3.

3. FY97 Research Goals

These goals are divided according to the section of the list on the previous page under which they fall.

- Item 1:
  - We will add at least one more domain to PRET — either viscoelastics or electronics. This is nontrivial, as it will require us to rework and probably augment the syntax with which coordinates and connections are described to the program. (Bradley, Easley)
  - We will rewrite the logic system to use backward reasoning; this should be much more efficient than the current forward-reasoning paradigm. (Stolle)
  - We will add rules as we test PRET on more examples in different domains. (Bradley, Easley, Hogan, Lawrence, Stolle)
  - We will continue improving PRET's automatic interaction with the ODRPACK parameter estimation package and write a paper about the issues and results, with our NIST colleagues, for presentation at the June 1997 Qualitative Reasoning Workshop in Italy. (Bradley, O'Gallagher, Rogers)
- Item 2:
  - We will begin work on a truth-maintenance system that will allow model refinement and simplification, and start to explore sensible and useful properties on which the algorithms and heuristics therein may be based. (Bradley, Easley, Stolle)
- Item 3:
  - We will implement at least one power-series technique, probably based on Volterra series, to generate hypotheses automatically. (Bradley, Hogan, Lawrence)
  - We will investigate various power-series methods, such as perturbation techniques, to infer internal state variables. (Bradley, Hogan, Lawrence)
  - We will draft a paper on the power-series results.
- Item 4:
  - We will set up the hardware and software for the data acquisition and control system and complete the interface that allows PRET to interact with this equipment. (Easley)
  - We will work out the syntax, semantics, and representation of the information PRET receives about the sensors. (Bradley, Easley)
  - We will fully automate PRET's input interactions. (Actuator representation and use and the implementation of the full *input/output* loop are much harder; this will be Easley's primary task for FY98.) (Bradley, Easley)
  - Easley will draft a Ph.D. proposal.

4. Technical Transitions

As of August 1996, only members of our project team have used the results of our work. We have already verified PRET's performance on some of the examples used in the graduate system identification course offered by the Aerospace Engineering Department at the University of Colorado; towards the end of this project, when PRET attains a high enough functional level, we plan to work with members of that department and test it on their research problems as well.

5. FY96 Research Accomplishments

- We presented a well-received paper and talk at the *Tenth International Workshop on Qualitative Reasoning* about the logic engine that forms PRET's core.
- We made significant improvements in the parameter estimation process, both in the ODRPACK package itself and in PRET's automatic interaction with it.
- A group of people ran PRET on a variety of non-toy examples.
- We developed some simple computer-vision code to analyze and classify patterns in sensor input (e.g., whether the time series reflects chaotic or periodic system behavior).

6. FY96 Publications and Submissions

[*] denotes work funded in part under this contract.

On this research project:

Elizabeth Bradley and Reinhard M. Stolle, "Automatic Construction of Accurate Models of Physical Systems," *Annals of Mathematics of Artificial Intelligence*, to appear.

Reinhard M. Stolle and Elizabeth Bradley, "A Logic Paradigm for Reasoning about Models," the *Tenth International Workshop on Qualitative Reasoning about Physical Systems*, Stanford Sierra Camp, 1996. [*]

On other research projects:

Elizabeth Bradley and Douglas E. Straub, "Using Chaos to Improve the Capture Range of a Phase-Locked Loop: Experimental Verification," to appear, *IEEE Trans. Circuits and Systems.*

Jonathan Dixon, Elizabeth Bradley, and Zoya Popović, "Nonlinear Time-Domain Analysis of Injection-Locked Microwave MESFET Oscillators," *IEEE Trans. on Microwave Theory and Technique*, in review.

7. Online Information

Available on my home page, `http://www.cs.colorado.edu/Homes/~lizb/Home.html`, are copies of most of my papers, along with short project descriptions intended to get graduate and undergraduate students interested in my research projects. No graphics for the PRET project exist on this page yet.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE 29-Aug-96	3. REPORT TYPE AND DATES COVERED Annual Report: 1 April 1996 - 30 August 1996

4. TITLE AND SUBTITLE Automatic Construction of Accurate Models of Physical Systems	5. FUNDING NUMBERS C/G N00014-96-1-0720 PR 96PR05164-00
6. AUTHOR(S) Elizabeth Bradley	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Colorado Department of Computer Science ECOT 717, CB 430 Boulder, CO 80309-0430	8.PERFORMING ORGANIZATION REPORT NUMBER None
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Nave Research Program Officer Michael Shneier ONR 311 Ballston Centre Tower One 800 N. Quincy Street, Arlington, VA 22217-5660	10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

None

12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for Public Release	12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report describes recent progress in the development of PRET, a computer program that automates the process of system identification. Given hypotheses, observations, and specifications, PRET constructs an ordinary differential equation model of a target system with no other inputs or intervention from its user. The core of the program is a set of traditional system identification (SID) methods. A layer of artificial intelligence (AI) techniques built around this core automates the high-level stages of the identification process that are normally performed by a human expert.

14. SUBJECT TERMS System Identification, Artificial Intelligence	15. NUMBER OF PAGES 5
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18.SECURITY CLASSIFICATION OF THIS PAGE	19.SECURITY CLASSIFICA OF ABSTRACT	20.LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unclassified

NSN 7540-01-280-5500

Standard Form 298 (Rev.23-89)
Prescribed by ANSI Std.239-18
298-102